Echoes of the fifth dimension?

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In this article we examine if the highest energy cosmic ray primaries could be ultra relativistic magnetic monopoles. The analysis is performed within the framework of large compact dimensions and TeV scale quantum gravity. Our study indicates that this hypothesis must be regarded as highly speculative but it cannot be ruled out.

This past year has seen a massive resurgence of interest in higher dimensional spacetimes [1], a key new concept being the localization of matter, and even gravity to branes embedded in extra dimensions [2]. Depending on the dimensionality and the particular form of this space, the long standing (Planck) hierarchy problem can find alternative solutions. In the canonical example of [3], the Planck scale of the four dimensional world is related to that of a higher dimensional space-time simply by a volume factor,

$$r = \left(\frac{M_{\rm pl}}{M_*}\right)^{2/n} \frac{1}{M_*}, \tag{1}$$

where $M_* \sim 1$ TeV is the fundamental scale of gravity [4], $M_{\rm pl} = 10^{18}$ GeV, and n is the number of extra dimensions. With this factorizable geometry the case of one extra dimension is clearly excluded since gravity would then be modified at the scale of our solar system. However, for $n \geq 2$, r is sufficiently small (the fundamental Planck scale is lowered all the way to TeV scale) and the model is not excluded by short distance gravitational measurements. A more compelling scenario requires curvature to spill into the extra dimension [5]. Within this framework the background metric is not flat along the extra coordinate, rather it is a slice of anti de Sitter space, due to a negative bulk cosmological constant balanced by the tension of two branes. In this non factorizable geometry, the curved nature of the spacetime causes the physical scale on the two branes to be different, and exponentially suppressed in the negative tension brane. Such exponential suppression can then naturally explain why the physical scales observed are so much smaller than the Planck scale. Variants of this solution have been discussed by many authors [6]. These models make dramatic predictions which can be directly confronted with current and future collider experimets [7] as well as cosmological observations [8]. The search for extra-dimension footprints in collider data has already started, however, no observational evidence has been found yet [9].

Another seemingly different, but perhaps closely related subject is the lack of a high energy cutoff in the cosmic ray (CR) spectrum. Over the last few years, several giant air showers have been detected [10] with no sign of the expected Greisen-Zatsepin-Kuz'min (GZK) cutoff [11]. Initiated by single high energy particles hitting the atmosphere, these are large pancake-shaped slabs of high energy particles which hit the ground at nearly the speed of light and can cover areas of many square kilometers. The origin and nature of the progenitors is, at present, a deep mystery [12]. Protons with energies above the GZK cutoff lose energy rapidly via inelastic collisions with the cosmic microwave background (CMB) and thus presumably must come from a nearby source. This seems unlikely [13]. Even though it was already noted that superheavy nuclei can evade the GZK cutoff [14], a typical nucleus of the cosmic radiation is subject to photodisintegration from blue-shifted microwave photons losing about 3-4 nucleons per traveled Mpc [15]. Gamma rays of the appropriate energy have a short mean free path for creating electron-positron pairs [16]. Although neutrinos can propagate through the CMB essentially uninhibited, at these energies the atmosphere is still transparent, and most of them interact in the Earth. The difficulties encountered in identifying a known particle as candidate have motivated suggestions in favor of "exotic" massive neutral hadrons, whose range is not limited by interactions with the CMB [17]. However, the latter predicts a correlation between primary arrival directions and the high redshift sources, which is not supported by the data set now available [18]. On a different track, it was recently put forward that extra dimensions may in principle hold the key to overcome this puzzle [19]. In this article we shall explore this fascinating possibility.

It has long been known that any early universe phase transition occurring after inflation (say with symmetry breaking temperature T_c), which leaves unbroken a $U(1)$ symmetry group, may produce magnetic monopoles [20]. For instance, minimal $SU(5)$ breaking may lead to "baryonic monopoles" of mass $M \sim T_c/\alpha$, with magnetic charge $U(1)_{\rm EM}$ and chromomagnetic (or color-magnetic charge) $SU(3)_{\rm C}$ [21]. Here α stands for the fine structure constant at scale T_c. These monopoles easily pick up energy from the magnetic fields permeating the universe and can traverse unscathed through the primeval radiation, thus, they are likely to generate extensive cascades [22].* Before proceeding further, it is important to point out that if the monopoles are formed at the usual grand unification scale (GUT) $\sim 10^{15}$ GeV, the energy density

*The idea of monopoles as constitutents of primary cosmic radiation is actually quite old, it can be traced back at least as far as 1960 [23].

overcloses the universe. Thus, to avoid this effect the symmetry breaking scale associated with the production of monopoles has to be shifted to lower energies. Remarkably, if the GUT scale is at $\sim 10^9$ GeV, one ends up with an abundance of relativistic monopoles well below the closure limit, and yet potentially measurable to explain the tail of the CR-spectrum. Moreover, for such critical temperature the observed flux of ultra high energy CRs is of the same order of magnitude as the flux allow by the Parker limit [24]. Unfortunately, contrary to the observed CR arrival directions, the expected flux of relativistic monopoles is highly anisotropic, pointing towards the magnetic lines near the Earth [25].

In the multidimensional models, the low-scale unification enables the production of light-mass monopoles, say $M \sim 100$ TeV. Furthermore, the physical embodiment of these theories allows a natural generalization of the 't Hooft-Polyakov monopole providing a convenient set of representations for D1-branes ending on D3-branes, and consequently even lighter monopoles. Namely, on the same line as in [22], giving a vacuum expectation value to a Higgs field in the **10** breaking $SU(5) \to SU(3) \times SU(2)$ lowers the monopole mass. Note, however, that direct searches at accelerators pretty much exclude masses below a few tens of GeV, whereas bounds stemming from quantum effects on current observables turn out to be much stronger ~ 1 TeV [26]. The light-mass monopoles could lose and gain energy as they random-walk towards the Earth. The maximum energy attainable before hitting the atmosphere is roughly 10^{25} eV [27]. Therefore, these "particles" would be ultra-relativistic, and the expected flux has no imprint of correlation with the local magnetic field.

From now on, we assume that ultra-relativistic monopoles strike the Earth's atmosphere generating a particle cascade, and we discuss in detail the most relevant observables of the showers, given from the analysis of both the particles at ground and those generated during the evolution of the cascade.

To simulate the monopole atmospheric cascade we shall adopt the model recently developed by Wick, Kephart, Weiler and Biermann (WKWB) [27], which ensures that if a baryonic-monopole hits the Earth it will penetrate deeply in the atmosphere, producing a heavy-particle-like cascade after the first interaction. It is mainly based on the four following axioms: i) before hitting the atmosphere the monopole-nucleus cross section is roughly hadronic $\sigma_0 \sim \Lambda_{\rm QCD}^{-2}$ (unstretched state), attaining a geometric growth after the impact; ii) in each interaction an $\mathcal{O}(1)$ fraction of the exchanged energy is devoted to stretch the chromomagnetic strings of the monopole; iii) the chromomagnetic strings can only be broken to create monopole-antimonopole pairs (a process highly supressed and consequently ignored); iv) the average fraction energy transferred to the shower in each interaction is soft $\Delta E/E \approx \Lambda_{\rm QCD}/M$.

We carried out a Monte Carlo simulation of monopole showers *à la* WKWB using the AIRES program (version 2.2.1) [28]. Namely, several sets of proton "clumps", each containing $M/\Lambda_{\rm QCD}$, were injected at 100 km.a.s.l with the first interaction fixed according to the proton mean free path. The sample was distributed in the energy range of 1×10^{18} eV up to 3×10^{20} eV, and was equally spread in the interval of $0°$ to $60°$ zenith angle at the top of the atmosphere. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons. The hadronic interaction was modelled with the SIBYLL package [29]. The results of these simulations were processed with the help of the AIRES analysis programs.

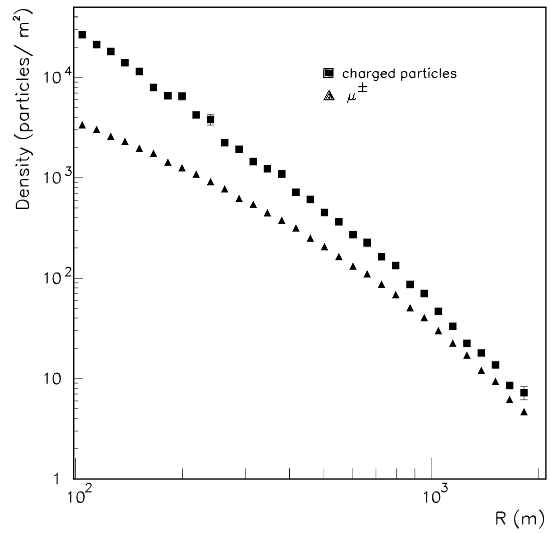

FIG. 1. Lateral distributions of charged particles and muons from AIRES simulations of a 100 EeV monopole with $M = 100$ TeV as a function of the distance to the shower core R. The error bars (obscured by the points themselves in most cases) indicate the RMS fluctuation of the means.

Resulting lateral distributions from a vertical incident monopole of 100 EeV (Lorentz factor $\equiv 10^6$) for muons and charged particles are presented in Fig. 1. A distinctive signature of this kind of shower is the great number of muons among all charged particles. This feature was observed in one not well understood "super-GZK" event [30]. Roughly speaking, a magnetic monopole could then be a likely primary for the highest energy Yakutsk event. However, WKWB-monopoles associated with a TeV unification scale certainly cannot explain the whole data at the end of the spectrum. This is illustrated in Figs. 2 and 3. In Fig. 2 we show the longitudinal development of monopole showers superimposed over the experimental data of the world's highest energy cosmic ray to date [31]. Clearly, by merely shifting the monopole mass to lower energies one can reproduce the atmospheric pro-

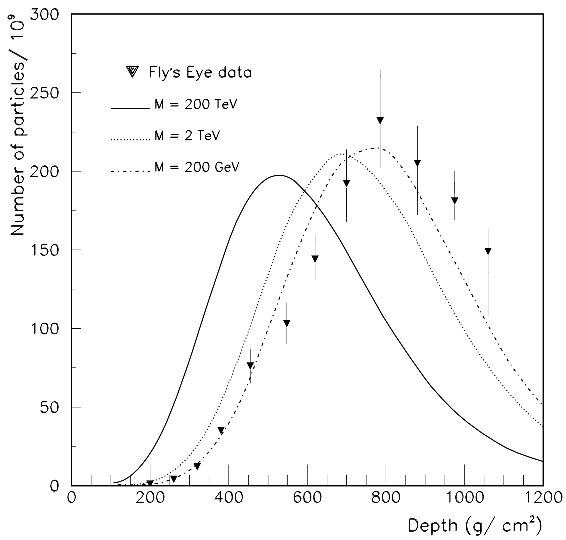

FIG. 2. Atmospheric cascade development of 300 EeV monopoles induced shower, superimposed over the Fly's Eye data.

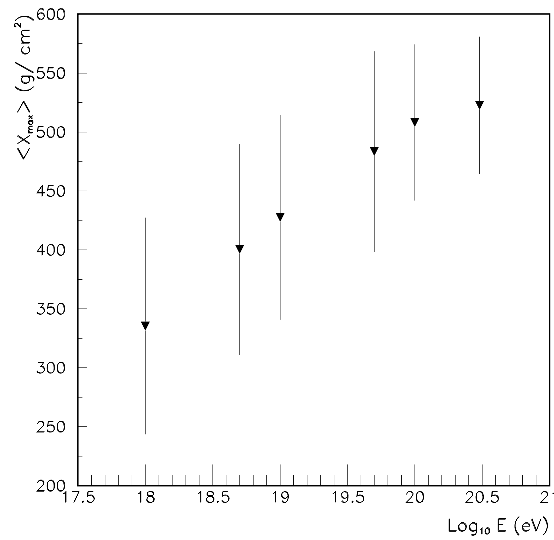

FIG. 3. Average slant depth of maximum of monopoles with $M \sim 100$ TeV. The error bars indicate the RMS fluctuations of the means.

file. Nevertheless, definite conclusions are precluded because of large fluctuations in the shower simulations. To handle this problem, we separately study each shower in the sub-sample of $M \sim 100$ TeV. Remarkably, after 58 simulations one obtains a late shower development: $< X_{\max} = 800 >$ gm/cm^2, consistent at 1 standard deviation with the scarce "super-GZK" data. A better understanding of the present situation needs the analysis of the evolution of the shower maximum $X_{\max}$ with energy. To this end, the charge multiplicity (essentially electrons and positrons) was used to determine the number of particles and the location of $X_{\max}$ by means of four parameter fits to the Gaisser-Hillas function [28]. The situation is summarized by displaying the mean $X_{\max}$ as a function of the logarithm of the primary energy in Fig. 3. It is clear that despite its deep penetration, the monopole cascade develops much faster than a proton shower [32]. The mean values in Fig. 3 are inconsistent with those recorded by the Fly's Eye experiment [33]. Again, notice that the situation could be improved by shifting the scale of the phase transition to lower energies.

Whether the laws of physics, in some deep realization, should be formulated in more than four dimensions, is something not yet clear. We expect and hope that with the help of data from future collider experiments the shower event generators could be improved. Furthermore, forthcoming ground arrays and satellites, such as the Auger Observatory [34], the next SCROD [35], and EUSO/OWL/AirWatch [36–38], will help to increase the CR sample and more exact limits on the air shower observables will be available, shedding light on the cool crazy ideas discussed in this paper.

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